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Pre-Production Solenoid for SS1 Section of HINS Linac

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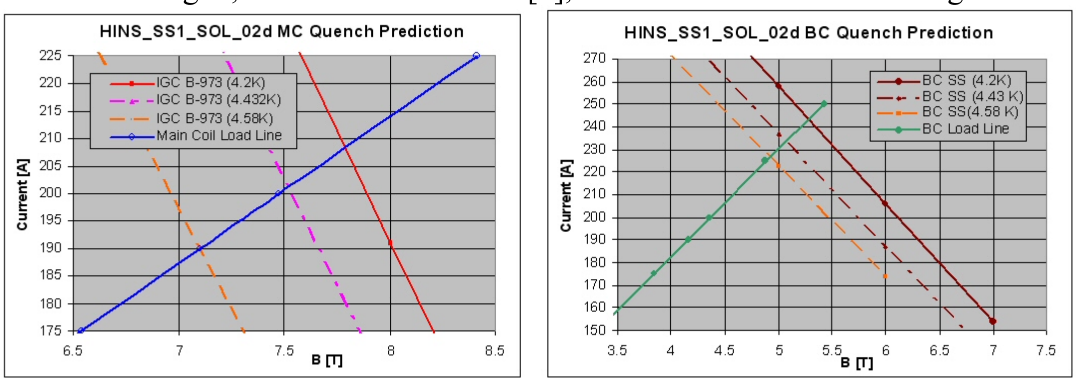
I. Introduction

The design of a focusing solenoid for the SS1 section of HINS linac was described in [1]. A prototype of this solenoid was tested on recently upgraded test stand #3 at TD Magnet Test Facility with a summary of results reported in [2]. As this test revealed, the new test environment resulted in a higher LHe operating temperature (4.43 K) due to a slightly higher system pressure. An even higher LHe temperature (4.58 K) is expected in the HINS linac cryostat in the Meson building. As a result, the quench current of the solenoid is shifted lower, which significantly reduces the current margin of the solenoids. The curves in Fig. 1, which are taken from [2], demonstrate this current margin reduction.



a) b)

Fig. 1. Quench current vs. magnetic field of the SS1 prototype solenoid wound with B-973 strand for different operating temperatures: a) Main coil, b) Bucking coils.

The quench current in the main coil, which is 209 A at 4.2 K, decreases to 201 A at 4.43 A and drops to ~190 A at the expected temperature of 4.58 K in the linac cryostat. With the nominal current of 175 A (see [1]), the current margin is only ~8.6%, which we consider insufficient. As a result, an adjustment to the existing design [1] is needed, which we describe in this note. Fig. 2 shows the original design, which serves as the starting point for further modifications.

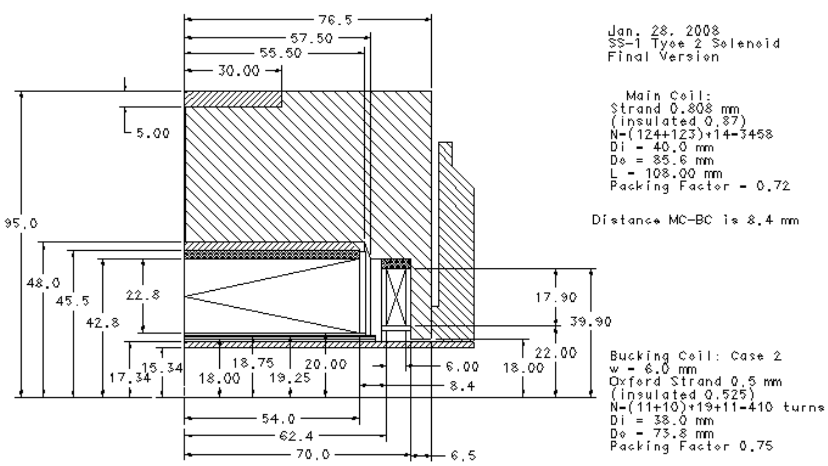


Fig. 2. SS1 Type 2 solenoid prototype design [1].

II. Pre-Production Solenoid Design

The design of the focusing solenoid must be modified to increase the current margin for B-973 strand to ~15% at the expected operating temperature of ~4.6 K. To achieve this margin, the length of the main coil (MC) of the solenoid must be increased by roughly 10%. The main coil and the bucking coils (BC) of the solenoid will be wound using the strand that was used to build the solenoid prototype [2]: IGC 0.808 mm strand (reel B-973) for the MC and 0.5 mm Oxford strand for the BC-s. The updated design is shown in Fig. 3.

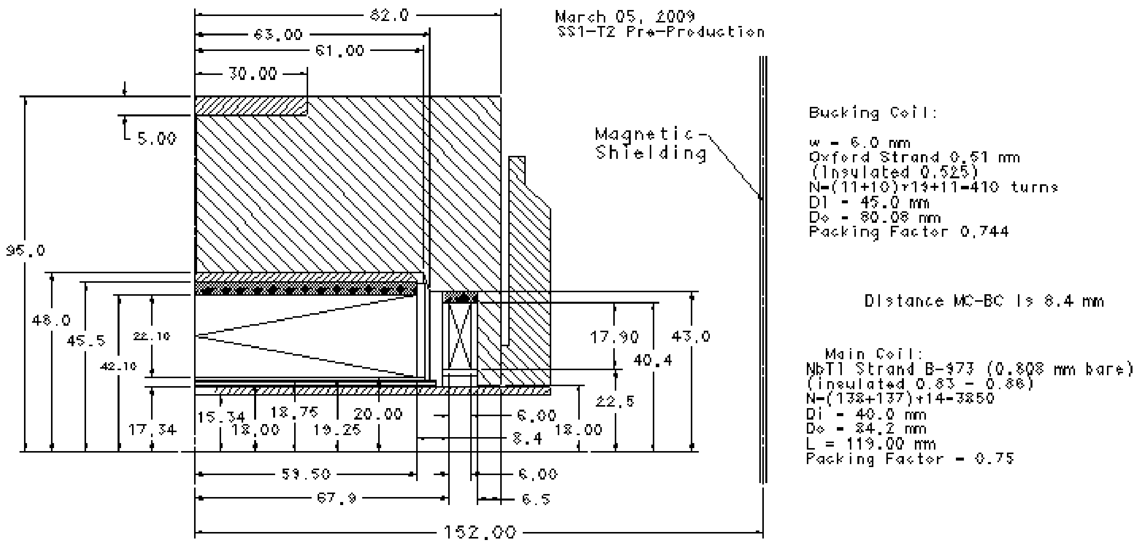


Fig. 3. SS-1 Type 2 pre-production focusing solenoid design

The main parameters of the solenoid are summarized in Table 1.

Table 1. As-Built SS1-T2 Prototype Main Coil Parameters

	Main coil	Bucking Coil
Coil I.D.	40 mm	45 mm
Coil O.D.	84.2 mm (average)	80.1 mm
Coil Length	119 mm	6 mm
Number of turns in the odd layers	138	11
Number of turns in the even layers	137	10
Number of layers	28	39
Total number of turns in the main coil	3850	410

At 200 A, the maximum field in the main coil of the solenoid is 7.66 T. In the bucking coil, the maximum field at this current is 4.46 T at the point R = 32.8 mm on the side which is closer to the main coil (Z = 67.9.mm). The quench diagram of the modified design is shown in Fig. 4.

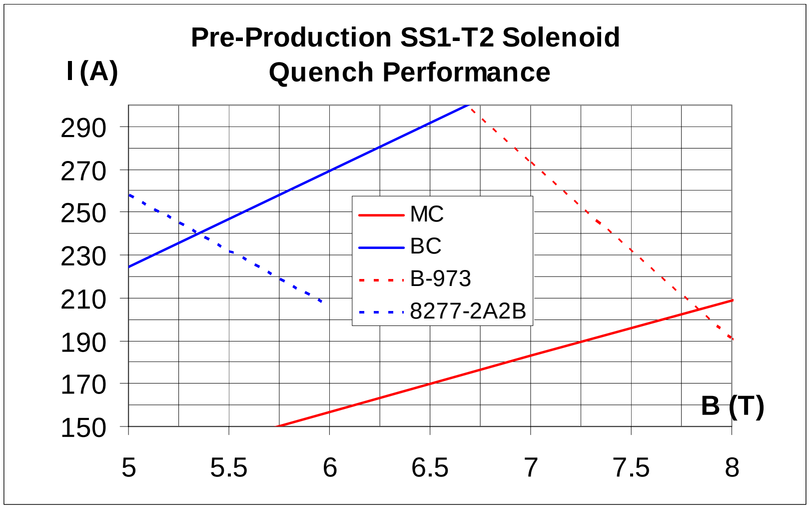
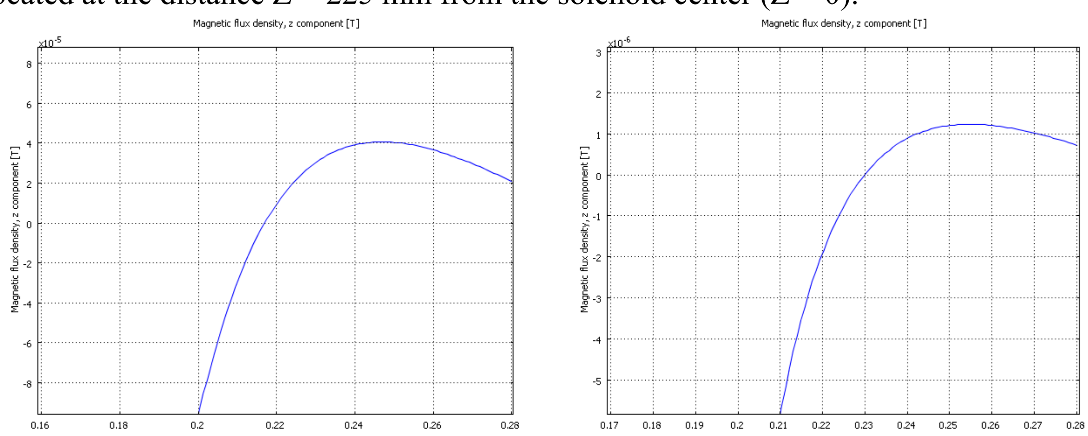


Fig. 4. Quench diagram of the pre-production solenoid at 4.2 K.

At 4.2 K, the device is expected to quench at 205 A with the quench in the main coil. The squared field integral $\int B^2 dz$ = 4.72 T^2-m at 200 A. To reach the required squared field integral of 3 T^2-m, a nominal current of 159.5 A must be applied, which results in a current margin of 28.6% at 4.2K. At 4.6 K, we can expect the quench current of ~186 A (225 A for the bucking coils), which leaves us with the margin of ~16%.

III. Fringe Field

For the SS1-T2 prototype solenoid, the distance along the axis between the center of the solenoid and the front shielding plate is 146 mm (as fabricated by Amuneal). Since the solenoid will be 11 mm longer, the new position of the shielding plate should be ~152 mm from the solenoid center. The fringe field along the axis of the solenoid at 200 A without shielding and with the shield is shown in Figures 5a and 5b. The cavity wall is located at the distance Z = 225 mm from the solenoid center (Z = 0).



a) b)

Fig. 5. The fringe field of the prototype SS-1 solenoid along the solenoid axis at 200 A: a) without magnetic shielding; b) with 1-mm shielding: μ = 10,000, Z_sh = 152 mm.

The graph in Fig. 6 shows the magnetic field in the transverse plane at Z = 225 mm, (the position of the wall of the superconducting cavity). There are three curves in the figure corresponding to different distances Z_sh from the center of the solenoid to the shielding front wall: 152 mm, 132 mm and 112 mm.

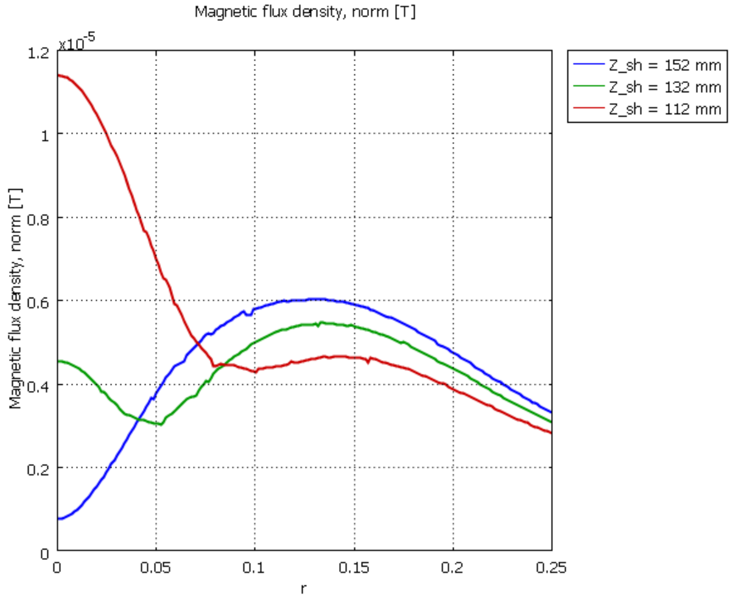


Fig. 6. Fringe magnetic field in the plane Z = 225 mm at 200 A.

Any of the three cases is acceptable, so the shield design can be relatively easily adapted to needs of the transition area. For the Z_sh = 112 mm case, the field is higher in the center than the allowed 10μT, but the cavity wall position is Z > 300 mm at this location, and the graph in Fig. 5b shows that the field will be lower at that distance. The magnetic field in the shield plate at 200 A for the case Z_sh = 112 mm does not exceed 0.25 T, which justifies the use of 1-mm thick Cryoperm-10 sheets (see Fig. 7).

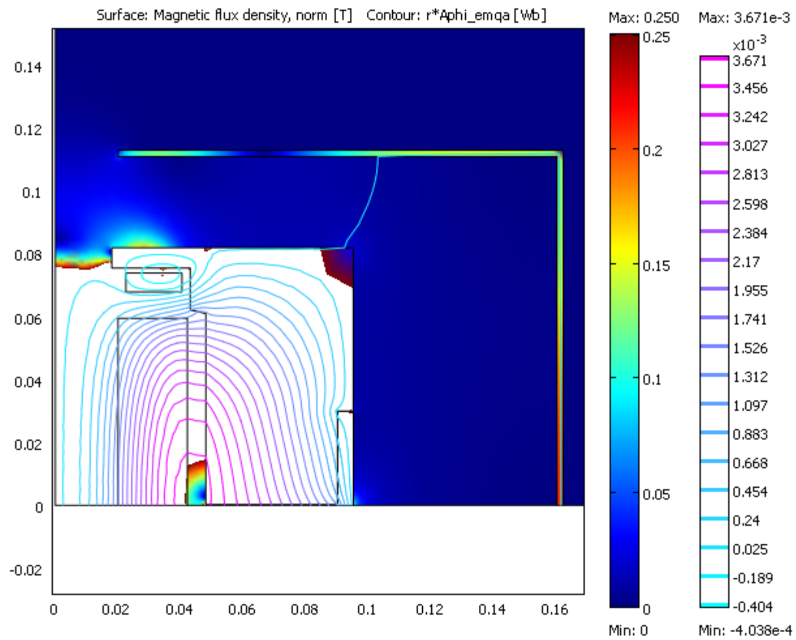


Fig. 7. Magnetic field in the solenoid shield (1-mm thick, μ = 10,000); Z_sh = 112 mm.

IV. Steering Coils

Steering coils are made similar to those in [1] and [2]. The only difference is a slight increase in length. This provides additional margin in the steering dipole strength, which was acceptable for the prototype. Fig. 8 shows general layout of a steering coil for the pre-production solenoid.

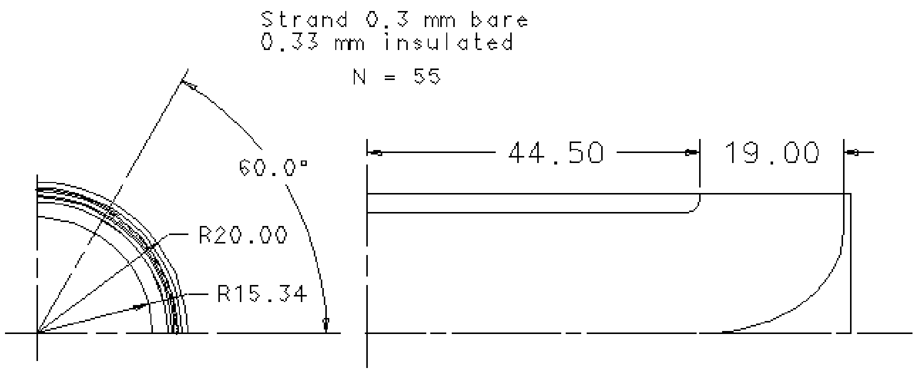


Fig. 8. General layout of the steering dipole winding

V. Quench protection issues

Quench protection issues for the SS1 prototype solenoid were addressed in [3]. Because the solenoid length and the number of turns have increased for the Pre-Production system, an update of the results obtained in [3] is needed. The same approach and the same tools were used to make the update. Fig. 9 shows a diagram of the maximum voltage developing during a quench event in different parts of the solenoid depending on the value of an energy extraction (aka "dump") resistor.

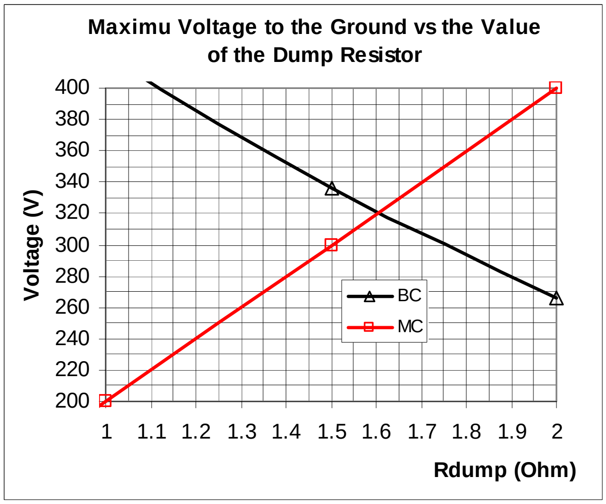


Fig. 9. Voltage in the MC and BC during quench as a function of the dump resistor value.

With an optimal resistance of 1.6 Ohm, the maximum voltage does not exceed 320 V, which is acceptable. With the 1.5 Ohm resistance, which was used in [2], the maximum voltage increases to ~340 V in the bucking coil, which is still acceptable.

The inductance of the main coil is ~0.3 H; the inductance of each bucking coil is ~0.015 H, which is a bit higher than it was in the prototype due to a larger inner radius (adjusted to obtain lower fringe field). The stored energy at 200 A is ~6 kJ.

VI. Conclusion

The modification of the SS1 section prototype solenoid design to a pre-production solenoid with better margin went quite smoothly. All requirement goals were met, including an increased temperature margin, an acceptable fringe field, and limits of voltage to ground during quench.

The solenoid will use strand reserved for the SS-1 solenoids production. The required number of solenoids to be built, including spares, is 22. The main coil of each solenoid contains ~800 m of superconducting strand, so the total amount of strand needed for production is ~17,500 m. The four reels with B-973 strand in our possession contain ~19,500 m of strand, which is sufficient for one pre-production solenoid and the required production solenoids.

References:

1. G. Davis, et. al, “HINS Linac SS-1 Section Prototype Focusing Solenoid Design”, TD-08-010, FNAL, March 2008.
2. G. Chlachidze, et. al, “HINS_SS1_SOL_02d Fabrication Summary and Test Results”, TD-09-001, FNAL, March 2009.
3. I. Terechkine, “Quench Protection Study for Focusing Solenoids of Superconducting Section of HINS Linac”, TD-09-002, February 2009.